

# *CP* violation and mixing in the charm sector at Belle, and current HFAG averages

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## 1 Introduction

Current HFAG averages of the mixing and *CP* violation (*CPV*) parameters in the  $D^0$  meson system is to be reviewed. We present recent Belle measurements of the mixing parameters  $x$  and  $y$  using  $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ , and  $y_{CP}$  and  $A_\Gamma$  from  $D^0 \rightarrow h^+ h^-$ ,  $D^0 \rightarrow K^- \pi^+$ , where  $h$  denotes  $K$  or  $\pi$ . Belle measurements of direct *CPV* in  $D^+ \rightarrow K_S^0 \pi^+$ ,  $D^0 \rightarrow h^+ h^-$ , and  $D^+ \rightarrow K_S^0 K^+$  decays together with  $\Delta A_{CP}^{hh}$  are to be presented.

## 2 Current HFAG averages [1]

$D^0 - \bar{D}^0$  mixing occurs since the mass eigenstates  $D_1$  and  $D_2$  are different from the weak eigenstates  $D^0$  and  $\bar{D}^0$ . Assuming *CPT* is conserved, the mass eigenstates can be written in terms of the weak eigenstates by  $|D_1\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$  and  $|D_2\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$ , where  $|p|^2 + |q|^2 = 1$ . Thus without *CPV*  $D_1$  and  $D_2$  are *CP*-even and *CP*-odd, respectively, with the HFAG convention  $CP|D^0\rangle = -|\bar{D}^0\rangle$  and  $CP|\bar{D}^0\rangle = -|D^0\rangle$ . The mixing parameters,  $x$  and  $y$  can be expressed by the difference of masses and widths between the two mass eigenstates,  $x = (m_1 - m_2)/\Gamma$  and  $y = (\Gamma_1 - \Gamma_2)/2\Gamma$ , where  $\Gamma = (\Gamma_1 + \Gamma_2)/2$ . *CPV* parameters are  $|q/p|$  and  $\phi = \text{Arg}(q/p)$ , where the former and the latter are responsible for *CPV* in mixing and that in interference between the decays with and without mixing, respectively. Without direct *CPV*, alternative mixing and *CPV* parameters are  $x_{12} = 2|M_{12}|/\Gamma$ ,  $y_{12} = |\Gamma_{12}|/\Gamma$ , and  $\phi_{12} = \text{Arg}(M_{12}/\Gamma_{12})$ , where  $M_{12}$  and  $\Gamma_{12}$  are off-diagonal elements of the  $D^0 - \bar{D}^0$  mass and decay matrices which are responsible for the mixing. Without *CPV*  $x_{12}$ ,  $y_{12}$ , and  $\phi_{12}$  become  $x$ ,  $y$ , and zero, respectively. Current HFAG averages of the mixing parameters  $x$ ,  $y$ ,  $x_{12}$ , and  $y_{12}$  rule out the no-mixing hypothesis with more than  $10\sigma$  significance, but they are difficult to be interpreted with the standard model (SM) due to the final state interactions [2]. *CPV* parameters,  $|q/p|$ ,  $\phi$ , and  $\phi_{12}$  show no indirect *CPV* at present. Since both  $x$  and  $y$  favor positive values, the *CP*-even state in the  $D^0$  system is heavier (unlike  $K^0$  system) and shorter-lived (like  $K^0$  system).

### 3 $CPV$ and mixing in the charm sector at Belle

#### 3.1 Mixing ( $x, y$ from $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ and $y_{CP}, A_\Gamma$ from $D^0 \rightarrow h^+ h^-$ and $D^0 \rightarrow K^- \pi^+$ )

Time dependent decay matrix element of  $D^0 \rightarrow K_S^0 \pi^+ \pi^-$  is expressed with

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2) \frac{e_1(t) + e_2(t)}{2} - \frac{q}{p} \bar{\mathcal{A}}(m_+^2, m_-^2) \frac{e_1(t) - e_2(t)}{2}, \quad (1)$$

where  $t$  is proper decay time,  $m_\mp^2 = m^2(K_S^0 \pi^\mp)$ ,  $e_j(t) = e^{-t(\Gamma_j/2 + im_j)}$ , and  $\mathcal{A}(\bar{\mathcal{A}})$  is the decay amplitude of  $D^0(\bar{D}^0)$ . Thus the mixing parameters,  $x$  and  $y$  can be extracted with time dependent Dalitz analysis of the decay rate,  $\mathcal{M}^2$ . The best fit model for  $\mathcal{A}(m_-^2, m_+^2)$  is found to be a sum of Breit-Wigner for P-, D-wave resonances, K-matrix [3] and LASS [4] models for  $\pi\pi$  and  $K\pi$  S-wave states, respectively, without non-resonant decay. Figure 1 shows the 2-D Dalitz plot and fit results as  $m_\mp^2$  and decay time projections. The results from the fit under  $CP$  conservation,  $q/p = 1$  and  $\mathcal{A} = \bar{\mathcal{A}}$ , are  $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$ ,  $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$ , and  $\tau_{D^0} = (410.3 \pm 0.4)$  fs, where  $x$  and  $y$  are the most sensitive to date and  $\tau_{D^0}$  is consistent with world average [5].

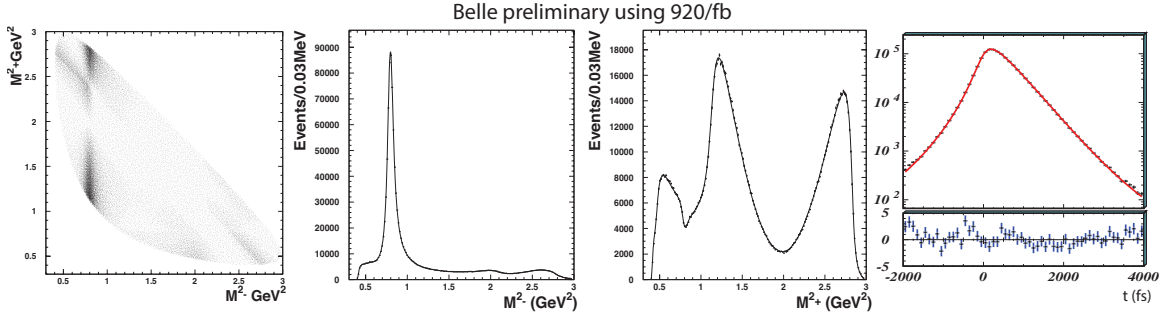


Figure 1: From left, 2-D Dalitz plot, fit projections onto  $m_-^2$ ,  $m_+^2$ , and proper decay time, respectively.

The width asymmetry between neutral  $D$   $CP$ -even and  $CP$ -odd eigenstates is referred to as  $y_{CP}$  and the experimental observable for  $y_{CP}$  is the lifetime difference between  $CP$ -even ( $D^0 \rightarrow h^+ h^-$ ) and  $CP$ -mixed ( $D^0 \rightarrow K^- \pi^+$ ) states as shown in Eq. (2). The  $y_{CP}$  could be different from  $y$  if  $CP$  is violated in charm decays.

$$y_{CP} = \frac{\Gamma(CP\text{-even}) - \Gamma(CP\text{-odd})}{\Gamma(CP\text{-even}) + \Gamma(CP\text{-odd})} = \frac{\tau_{D^0 \rightarrow K^- \pi^+}}{\tau_{D^0 \rightarrow h^+ h^-}} - 1 \simeq y. \quad (2)$$

The width asymmetry between two  $CP$  conjugate modes provides the  $CPV$  parameter,  $A_\Gamma$  which can be measured from lifetime difference between the two  $CP$

conjugate decays. Figure 2 show the results for  $y_{CP}$ ,  $A_\Gamma$ , and  $\tau_{D^0 \rightarrow K^- \pi^+}$  as a function of the  $\cos \theta^*$ , where  $\theta^*$  is polar angle of  $D^0$  at the center-of-mass system (c.m.s.). The averages are  $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$ ,  $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$ , and  $\tau_{D^0 \rightarrow K^- \pi^+} = (408.56 \pm 0.54)$  fs, where the last is consistent with world average [5]. Thus we observe  $y_{CP}$  with  $4.5\sigma$  significance and find no  $CPV$ .

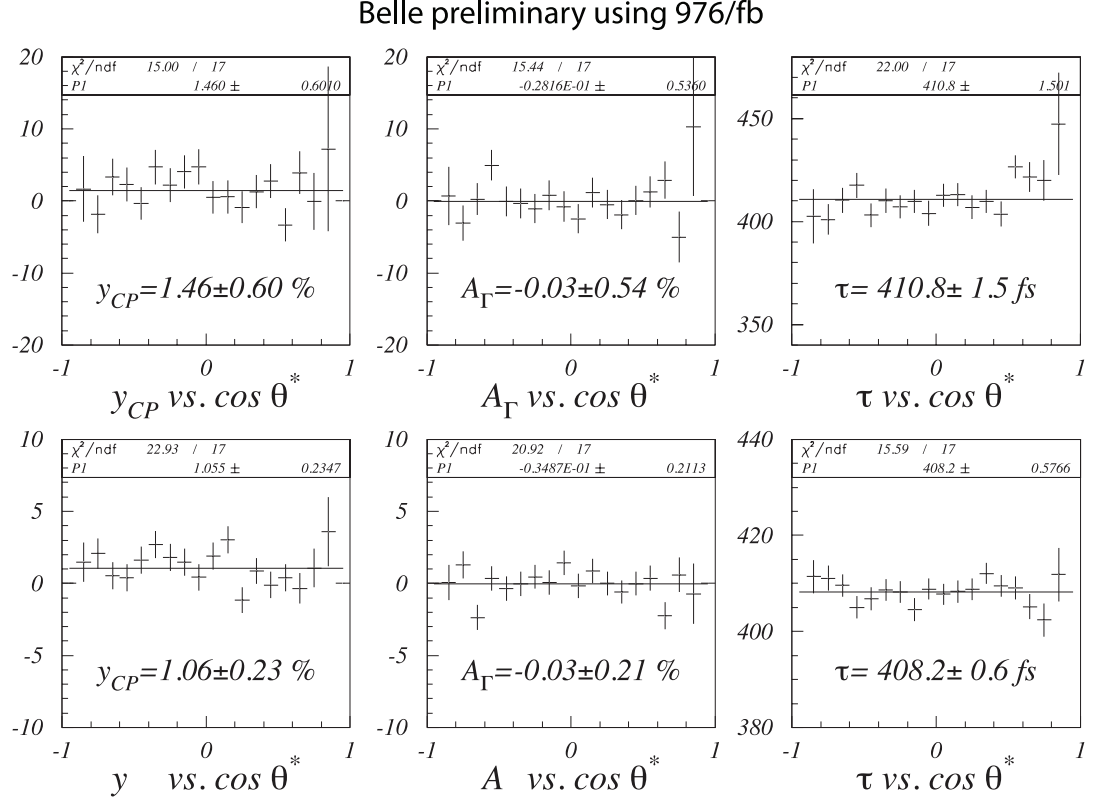


Figure 2:  $y_{CP}$ ,  $A_\Gamma$ , and  $\tau_{D^0 \rightarrow K^- \pi^+}$  as a function of the  $\cos \theta^*$ . Top(bottom) three plots are obtained with 3-layer(4-layer) silicon detector.

### 3.2 Direct $CPV$ ( $A_{CP}$ in $D^+ \rightarrow K_S^0 \pi^+$ , $D^0 \rightarrow h^+ h^-$ , $D^+ \rightarrow K_S^0 K^+$ , and $\Delta A_{CP}^{hh}$ )

The  $D^+ \rightarrow K_S^0 \pi^+$  final state is a coherent sum of Cabibbo-favored and doubly Cabibbo-suppressed decays where no SM  $CPV$  in charm decay is expected, while  $(-0.332 \pm 0.006)\%$  [5] of  $A_{CP}^{\bar{K}^0}$ <sup>1</sup> is expected. Using  $\sim 1.74$ M reconstructed  $D^+ \rightarrow K_S^0 \pi^+$

<sup>1</sup>Here,  $A_{CP}^{\bar{K}^0}$  denotes  $CPV$  due to  $K^0 - \bar{K}^0$  mixing.

decays, the  $A_{CP}$  is measured in bins of  $|\cos \theta_{D^+}^{c.m.s.}|$  and the average of  $A_{CP}^{D^+ \rightarrow K_S^0 \pi^+}$  is  $(-0.363 \pm 0.094 \pm 0.067)\%$  which shows  $3.2\sigma$  deviations from zero. This is the first evidence for  $CPV$  in charm decays from a single decay mode while the measured asymmetry is consistent with the  $A_{CP}^{\bar{K}^0}$ . After subtracting experiment dependent  $A_{CP}^{\bar{K}^0}$  [6], the  $CPV$  in charm decay,  $A_{CP}^{D^+ \rightarrow \bar{K}^0 \pi^+}$ <sup>2</sup>, is measured to be  $(-0.024 \pm 0.094 \pm 0.067)\%$  [7].

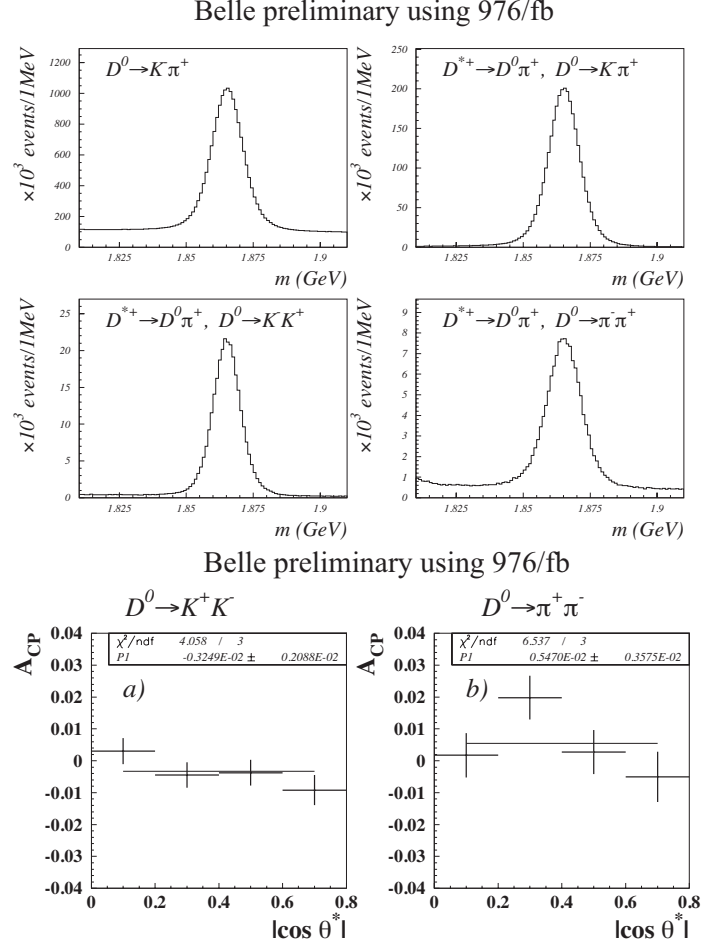


Figure 3: Top four plots show reconstructed signal distributions described in the text and bottom two plots show preliminary results of  $A_{CP}$  as a function of the polar angle of  $D^{*+}$  momentum at the c.m.s.

The  $D^0 \rightarrow h^+ h^-$  final states are singly Cabibbo-suppressed (SCS) decays in which both direct and indirect  $CPV$  are expected in the SM [8], while the  $CP$  asymmetry

<sup>2</sup>We neglect doubly Cabibbo-suppressed decay,  $D^+ \rightarrow K^0 \pi^+$ .

difference between the two decays,  $\Delta A_{CP}^{hh} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$  reveals approximately direct  $CPV$  with the universality of indirect  $CPV$  in charm decays [9]. Figure 3 shows reconstructed signal distributions showing 14.7M  $D^0 \rightarrow K^-\pi^+$ , 3.1M  $D^{*+}$  tagged  $D^0 \rightarrow K^-\pi^+$ , 282k  $D^{*+}$  tagged  $D^0 \rightarrow K^+K^-$ , and 123k  $D^{*+}$  tagged  $D^0 \rightarrow \pi^+\pi^-$ , respectively, and the measured  $A_{CP}$  in bins of  $|\cos\theta_{D^{*+}}^*|$ . From the bottom plots in Fig. 3, we obtain  $A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$  and  $A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$  where the former shows the best sensitivity to date. From the two measurements, we obtain  $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$  which shows  $2.1\sigma$  deviations from zero and supports recent LHCb [10] and CDF [11] measurements. By combining LHCb, CDF, and Belle results, the average of  $\Delta A_{CP}^{hh}$  becomes  $(-0.74 \pm 0.15)\%$ .

The  $D^+$  decaying to the final state  $K_S^0 K^+$  proceeds from  $D^+ \rightarrow \bar{K}^0 K^+$  decay which is SCS, where direct  $CPV$  is predicted to occur [8]. The decay  $D^+ \rightarrow \bar{K}^0 K^+$  shares the same decay diagrams with  $D^0 \rightarrow K^+ K^-$  by exchanging the spectator quarks,  $d \leftrightarrow u$ . Therefore, neglecting the helicity and color suppressed contributions in  $D^+ \rightarrow \bar{K}^0 K^+$  and  $D^0 \rightarrow K^+ K^-$  decays, the direct  $CPV$  in the two decays is expected to be effectively the same. Thus, as a complementary test of the current  $\Delta A_{CP}^{hh}$  measurement, the precise measurement of  $A_{CP}$  in  $D^+ \rightarrow \bar{K}^0 K^+$  helps to pin down the origin of  $\Delta A_{CP}^{hh}$  [12]. Figure 4 shows invariant masses of  $D^\pm \rightarrow K_S^0 K^\pm$  together with the fits that result in  $\sim 277k$  reconstructed decays and the measured  $A_{CP}$  in bins of  $|\cos\theta_{D^+}^{c.m.s.}|$ . From the right plot in Fig. 4, we obtain  $A_{CP}^{D^+ \rightarrow K_S^0 K^+} = (-0.246 \pm 0.275 \pm 0.135)\%$ . After subtracting experiment dependent  $A_{CP}^{\bar{K}^0}$  [6], the  $CPV$  in charm decay,  $A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+}$ , is measured to be  $(+0.082 \pm 0.275 \pm 0.135)\%$ . The current average of  $\Delta A_{CP}^{hh}$  measurements as well as the Belle preliminary result of  $A_{CP}^{KK}$  favor a negative value. Our result, on the other hand, does not show this tendency for  $D^+ \rightarrow \bar{K}^0 K^+$  decays, albeit with a significant statistical uncertainty.

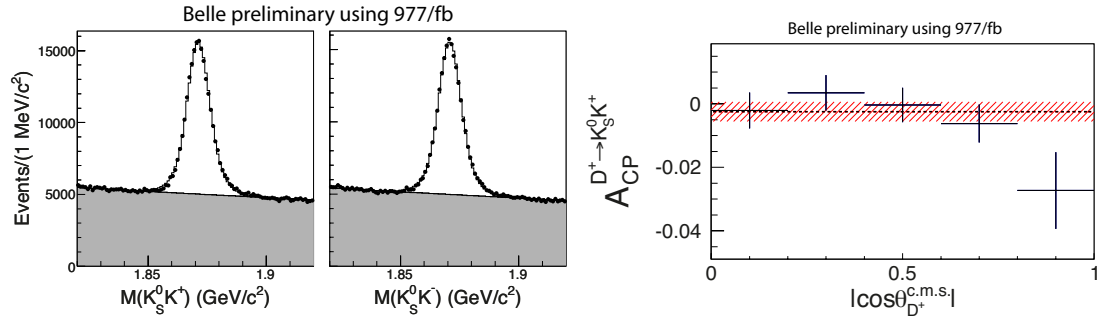


Figure 4: Left two plots show  $M(K_S^0 K^+)$  and  $M(K_S^0 K^-)$  distributions, respectively, and right plot shows preliminary result of  $A_{CP}$  as a function of the polar angle of  $D^+$  momentum at the c.m.s.

## 4 Summary

In summary, we review the current HFAG averages of  $CPV$  and mixing parameters in the charm sector and recent relevant measurements from Belle. Belle measurements of mixing and  $CPV$  parameters are consistent with current HFAG averages. No direct  $CPV$  in charm decays has been observed from Belle to date.

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